SMALL SPACECRAFT TECHNOLOGY PLAN
2020 SBIR INNOVATION & OPPORTUNITY CONFERENCE

EXPLORE
SMALL SPACECRAFT

SMALL, RAPID, AFFORDABLE & TRANSFORMATIVE

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WHY ARE WE (VIRTUALLY) HERE

- NASA believes small spacecraft have the potential to shape how the agency approaches what is possible
- Achieving these desired future states (“Outcomes”) will likely leverage rapid development and costs below those of traditional missions
- There is no single technical solution – many Technology Gaps have been identified and realizing these Outcomes will require combinations of innovations
- Closing the identified Technology Gaps will move us towards achieving the desired Outcomes
- NASA is currently developing a priority order to those Technology Gaps so that resources can be invested strategically on solutions that have:
    - The highest “Architectural” applicability to stakeholders within NASA and small spacecraft community
    - The largest impact on achieving the desired Outcomes
- NASA will fund these priorities through future STMD funding opportunities, including SBIR subtopics

STMD SMALL SPACECRAFT TECHNOLOGY CAPABILITY AREA

NASA is pursuing rapid identification, development, and testing of capabilities that exploit ***agile spacecraft platforms and responsive launch*** capabilities to increase the pace of space exploration, scientific discovery, and the expansion of space commerce.

These emerging capabilities have the potential to enable new mission architectures, enhance conventional missions, and promote development and deployment on faster timelines. This will, in turn, allow NASA to achieve its objectives at significantly lower programmatic risk and cost than traditional approaches.

The plan is largely focused on technology gaps for ***CubeSats and microsatellites*** that use standardized form factors, interchangeable commercial components, and can be batch produced.

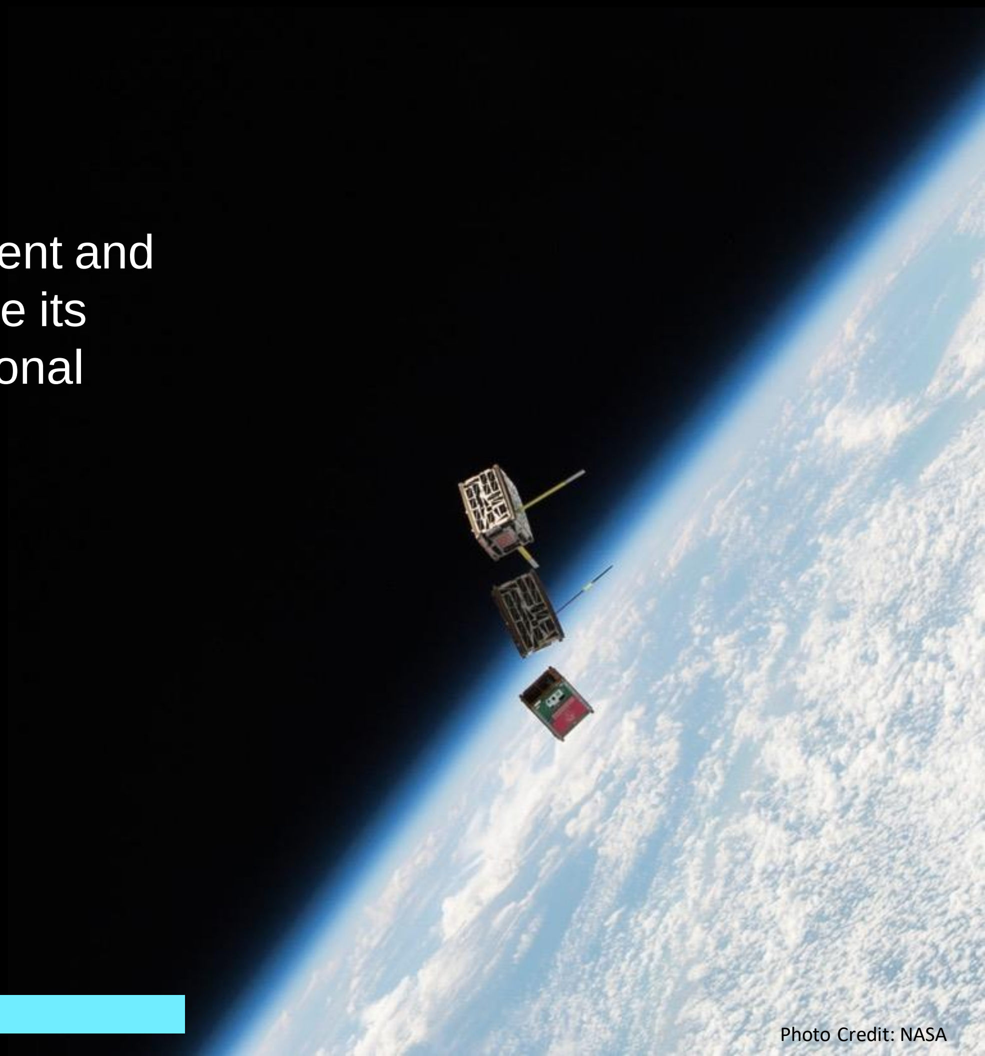


Photo Credit: NASA

BASED ON DRAFT PLAN · SUBJECT TO CHANGE

STMD SMALL SPACECRAFT TECHNOLOGY ARCHITECTURAL APPLICABILITY

MOONtoMARS

Exploration Architectures for Human Lunar Return, Sustained Human Presence, & First Human Mars Expedition

Small spacecraft afford an increasingly capable platform to precede and accompany human explorers to the Moon, Mars, and other destinations to scout terrain, characterize the environment, identify risks, and prospect for resources. Distributed systems of small spacecraft can responsively provide cost-effective communications, monitoring, and inspection infrastructure for human exploration missions and cislunar commercial activity.

SOLAR SYSTEM&BEYOND

Scientific Discovery Architectures for Earth, Planetary, Heliophysics, & Astrophysics

The affordability and speed of small spacecraft allows more missions to more destinations of scientific interest. Additionally, the use of small spacecraft as affordable distributed systems can enable new science measurements in deep space and around planetary bodies that are not attainable using traditional approaches

SPACE TECH

Technology Demonstration, Commercial, and National Security Architectures

NASA’s overarching technology goals for its engagement in the small spacecraft ecosystem are to enable rapid and more affordable missions for exploration and discovery while facilitating the expansion of space commerce.

DESIRED FUTURE STATES ("OUTCOMES") RELATED TO SMALL SPACECRAFT CAPABILITIES

GO "OUTCOMES"

- Affordable on demand access to the Moon, Mars, the rest of the inner planets, and other deep space destinations this side of the asteroid belt. (*Target: Under $15M with multiple opportunities per year.*)
- Access to the outer planets, their moons, and beyond for small missions.

EXPLORE "OUTCOMES"

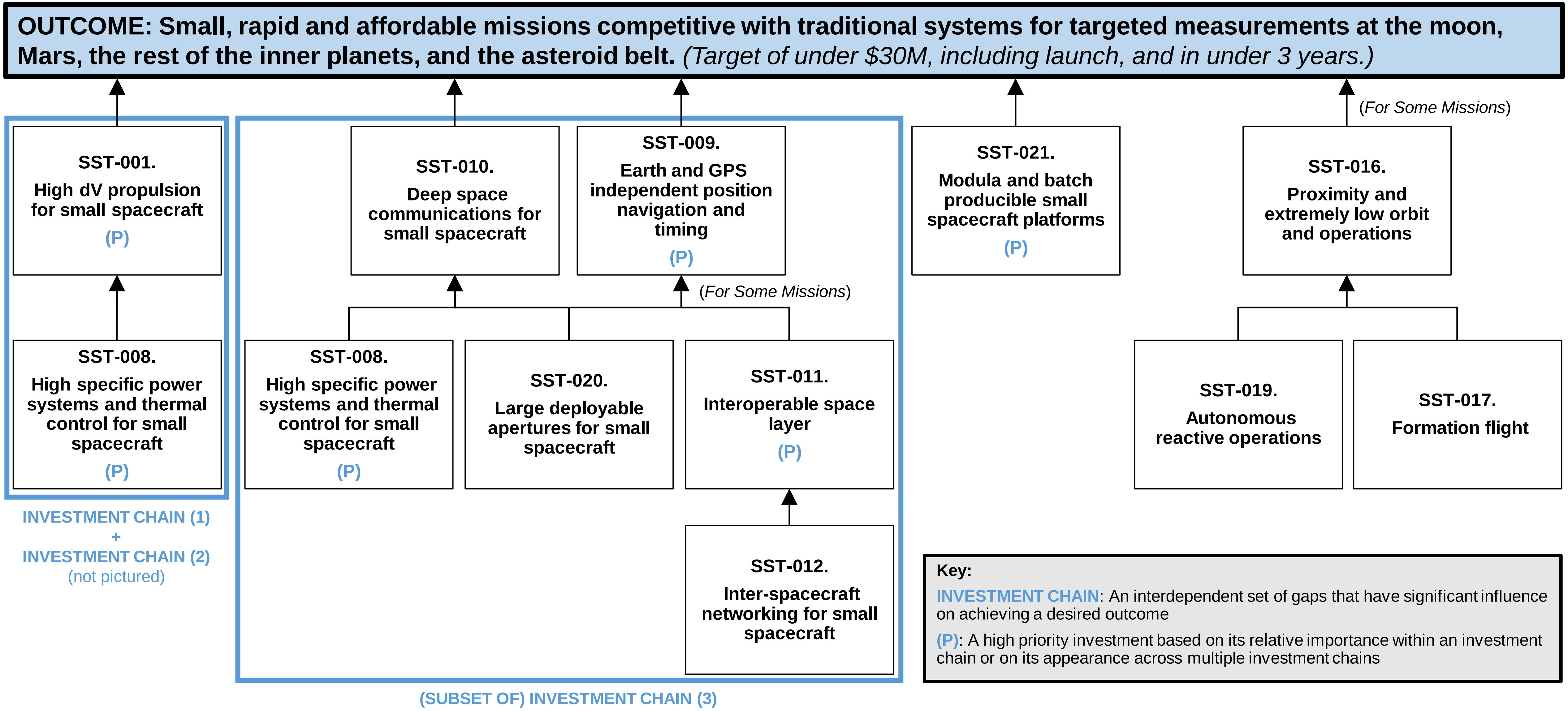
- Small, rapid and affordable missions competitive with traditional systems for targeted measurements at the Moon, Mars, the rest of the inner planets, and the asteroid belt. (*Target: Under $30M, including launch, and developed in under 3 years.*)
- Affordable, modular, and interoperable communications, navigation, and support infrastructure with full coverage of the Moon and Mars. (*Target: Under $20M to build and deliver each network node.*)
- Affordable distributed missions of at least 30 to 100 networked spacecraft acting as a sensor web in deep space. (*Target: Under $10M to build and deliver each node.*)
- Affordable deep space capable distributed systems that can form multi-kilometer wide synthetic apertures and multi-kilometer long virtual telescopes. (*Target: Under $20M to build and deliver each element.*)
- Small spacecraft able to accompany and augment larger missions to the outer planets and their moons.

LEAD "OUTCOMES"

- Rapid in space test capabilities that allow a technology to move from laboratory to orbit in less than 9 months.

BASED ON DRAFT PLAN · SUBJECT TO CHANGE

SELECT TECHNOLOGY DEVELOPMENT PATH EXAMPLE



SST-001. HIGH dV PROPULSION FOR SMALL SPACECRAFT (P)

Enabling many of the deep space missions envisioned for multiple classes of small spacecraft requires approximately 2 to 5 km/s dV over the multiyear life of a mission. To enable that level of propulsive capability in CubeSats, systems are required that have a high impulse per unit of spacecraft and high total impulse, while remaining low power per unit of spacecraft and compatible with secondary payload launch restrictions.

A FEW KEY ELEMENTS:

- At least 2 km/s dV
- High impulse per unit of spacecraft and high total impulse
- Low power per unit of spacecraft
- Compatible with secondary payload launch restrictions
- Tolerant to the deep space radiation and thermal environment over a multiyear mission
- For CubeSats use of high-density propellant may be needed to achieve the required performance within volume limitations.
- Microsatellite scale systems have relaxed size, weight, and power constraints but need increased thrust levels

SELECT TECHNOLOGY GAP DETAILS

SST-009. EARTH AND GPS INDEPENDENT POSITION NAVIGATION AND TIMING (P)

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth centric aids. Future small spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions, for distributed missions comprised of small spacecraft, and for standalone small spacecraft missions beyond Earth.

A FEW KEY ELEMENTS:

- Navigation technologies and techniques may include inertial navigation combined with…
  - Enhanced visual navigation capabilities
    (Like dual use of star tracking instruments for relative navigation using surface features or other spacecraft)
  - X-ray emissions (from pulsars)
  - Laser range finding with other spacecraft or surface landmarks.
- Compatible with the inherent size, weight, power, and cost constraints of CubeSats & microsatellites.
- Onboard image and data processing is required to allow for autonomous navigation.
- Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data.

SELECT TECHNOLOGY GAP DETAILS

SST-021. MODULAR AND BATCH PRODUCIBLE SMALL SPACECRAFT PLATFORMS (P)

Interchangeable hardware and software with standardized interfaces enable spacecraft to be built up from "plug and play" components. This facilitates introduction of new capabilities and tailoring of spacecraft designs for novel applications without requiring significant modifications to commercial-off-the-shelf platforms. Modularity can be used to increase reliability and introduce unique functionality for deep space missions without sacrificing the ability to leverage innovations in the commercial sector. Partnership with industry on batch production of spacecraft will be required to fully realize the potential for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications architectures, constellations, and sensor web applications.

A FEW KEY ELEMENTS:

- Standardization of subsystem interfaces can help enable unique mission configurations with COTS hardware

  (Expand the reach of small spacecraft to new destinations without losing the speed and agility that has made the platform highly successful in LEO)
- Extend standardization principles into larger microsatellites
- Affordable and adaptable methods of addressing radiation tolerance / thermal environment
- Reduce spacecraft manufacturing complexity
- Regular production of low-cost and shorter lead time (< 12 months) platforms that can be made deep space capable

HOW TO LEVERAGE THE SMALL SPACECRAFT TECHNOLOGY PLAN

- This plan is **still a draft** and subject to change…
- Goals of the plan include:
  - Clearly communicating NASA needs
  - Helping NASA prioritize future solicitations / investments on the technologies that are most impactful
  - Helping proposers identify where their technology development efforts algin with NASA priorities
- Full draft of Outcomes & Technology Gaps (presentation version) is attached for reference
- Small spacecraft community feedback on draft plan is desired
  - Targeting an RFI in early October

EXPLORE SPACE TECH

WITH SMALL SPACECRAFT

The Small Spacecraft Technology (SST) program expands the ability to execute unique missions through rapid development and demonstration of capabilities for small spacecraft applicable to exploration, science and the commercial space sector.

Notes for SBIR companies

- SST often leverages SBIR-developed technologies and brings them to flight
- SBIR companies should stay aware of the program's activities and opportunities

LEARN MORE: WWW.NASA.GOV/DIRECTORATES/SPACETECH/SMALL_SPACECRAFT

EXPLORE SPACE TECH

THROUGH SUBORBITAL FLIGHT

The Flight Opportunities (FO) program facilitates rapid demonstration of promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital testing with industry flight providers

Notes for SBIR companies

- Annual Tech Flights solicitation provides awards to fund suborbital flight tests with commercial providers
- Companies with a SBIR Phase I award are eligible to request FO facilitate suborbital testing via a Phase III
- FO can be an external investor in a Post Phase II activity that includes suborbital testing

Photo Credit: Blue Origin

LEARN MORE: WWW.NASA.GOV/DIRECTORATES/SPACETECH/FLIGHTOPPORTUNITIES

NASA

REFERENCE MATERIAL:
DRAFT SMALL SPACECRAFT TECHNOLOGY PLAN
(PRESENTATION VERSION)

CAUTION: THIS IS A DRAFT

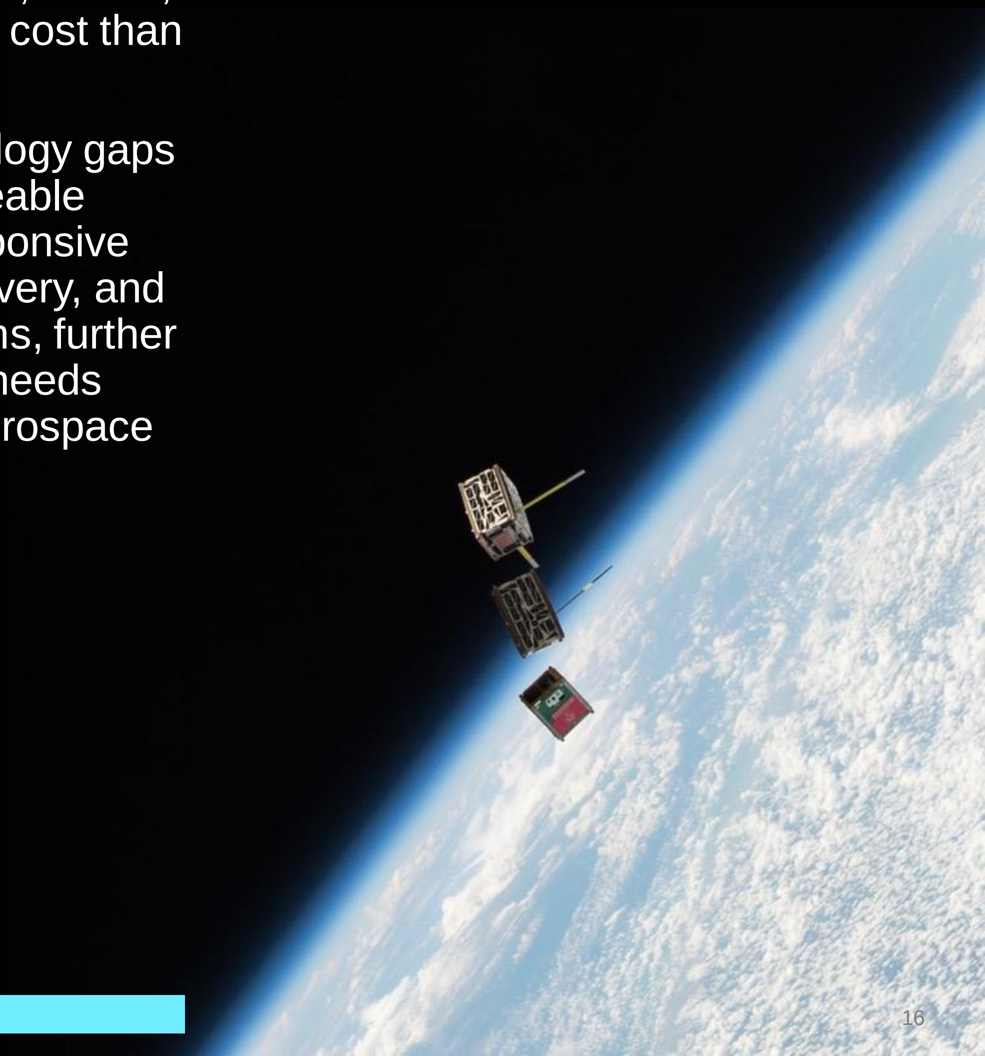
CAUTION THIS IS STILL A DRAFT AND SUBJECT TO CHANGE

- Development of the Small Spacecraft Technology Plan is an on going process. This presentation is based on the 09-14-2020 DRAFT.
- The scope is currently CubeSats other nanosatellites and microsatellite scale spacecraft. STMD has historically considered 180kg as the upper mass limit for a small spacecraft.
- Targeted Outcomes are subject to revision or consolidation.
- Technical Gaps are undergoing internal review as of the development of this presentation. Cited performance parameters may change or additional parameters may be added. Additional community feedback will be sought.
- The internal prioritization process is on going as of the development of this presentation and the current prioritization of the Technical Gaps may change.

1.1 DESCRIPTION AND SCOPE

NASA is pursuing rapid identification, development, and testing of capabilities that exploit agile spacecraft platforms and responsive launch capabilities to increase the pace of space exploration, scientific discovery, and the expansion of space commerce. These emerging capabilities have the potential to enable new mission architectures, enhance conventional missions, and promote development and deployment on faster timelines. This will, in turn, allow NASA to achieve its objectives at significantly lower programmatic risk and cost than traditional approaches.

This small spacecraft technology development plan is largely focused on technology gaps for CubeSats and microsatellites that use standardized form factors, interchangeable commercial components, and can be batch produced. Small spacecraft and responsive launch capabilities are proving to be disruptive innovations for exploration, discovery, and commercial applications. As these innovations move up market to larger platforms, further technology and capability investment will be needed to meet upcoming mission needs while keeping overall costs low, mission cadence high, and retaining the agile aerospace approach that has fueled what has been termed the “smallsat revolution”.



1.2 ARCHITECTURAL APPLICABILITY

MOON to MARS

MOON TO MARS EXPLORATION ARCHITECTURE

Human Lunar Return, Sustained Human Presence, & First Human Mars Expedition

Small spacecraft afford an increasingly capable platform to precede and accompany human explorers to the Moon, Mars, and other destinations to scout terrain, characterize the environment, identify risks, and prospect for resources. Distributed systems of small spacecraft can responsively provide cost-effective communications, monitoring, and inspection infrastructure for human exploration missions and cislunar commercial activity.

- Terrestrially focused small spacecraft capabilities can be leveraged to establish **communications, navigation, and logistical** infrastructure for the lunar and Martian surface.
- The lower overall mission cost of small spacecraft is attractive for pathfinding and prospecting missions to **map resources, tomography, and surface features** to assist with ISRU and identification of potential landing hazards on the Moon and Mars.

SOLAR SYSTEM & BEYOND

SCIENTIFIC DISCOVERY ARCHITECTURES

Earth, Planetary, Heliophysics, & Astrophysics

The affordability and programmatic speed of small spacecraft allows more missions to more destinations of scientific interest. Additionally, the use of small spacecraft as affordable distributed systems can enable new science measurements in deep space and around planetary bodies that are not attainable using a traditional approach.

- Market forces are driving small spacecraft technologies for Earth orbiting missions, however, there are crosscutting and strategically important multi-spacecraft architectures that warrant NASA investment to enable synthetic apertures, long baseline interferometry, and **persistent planetoid coverage**.
- Expendable small spacecraft probes can make **targeted measurements** at the Moon, Mars, Venus, and Near Earth Objects and, coupled with reactive launch, allow access to transient or temporary phenomena throughout the solar system.
- Small spacecraft can enable affordable **multipoint measurement of time variant phenomena** important to heliophysics and space weather prediction, be used for magnetic field mapping and gravitational studies, or act as sensor webs to catch transient events.
- Greater observatory power may be achievable through distributed systems that form **synthetic apertures** many times larger than the individual components.

1.2 ARCHITECTURAL APPLICABILITY (cont.)

COMMERCIAL ARCHITECTURES

The number of commercial small spacecraft operators and the number of small spacecraft being operated for commercial services significantly exceeds their government counterparts. As of 2020, the majority of commercial small spacecraft were Earth observation platforms. This is anticipated to remain the dominant application for the nanosatellite and small microsatellite scale. In the larger microsatellite scale, communications services became the dominate use in 2019.

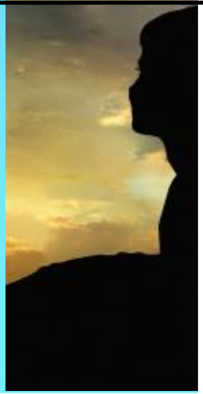
- NASA should **remain cognizant of commercial endeavors**, make use of **standardized spacecraft and parts** developed for commercial applications in place of mission-specific solutions where possible, and **partner with industry** to target NASA relevant gaps that are adjacent to commercial needs but that market forces will not otherwise fill.

NATIONAL SECURITY ARCHITECTURES

Civil and national security space share many of the same small spacecraft technology and capability needs. Collaborative opportunities and engagement between NASA and other US Government entities can help reduce technical and programmatic risk on future missions.

- Key areas of commonality include the need for **industrial resilience and operational reliability**, communications and **inter-spacecraft networking** technologies, advanced remote sensing capabilities for small spacecraft, **navigation and timing** for small spacecraft that does not rely on GPS, on-orbit **autonomy** and management of distributed missions, and **responsive access to space**.

SPACE TECH



TECHNOLOGY DEMONSTRATION ARCHITECTURES

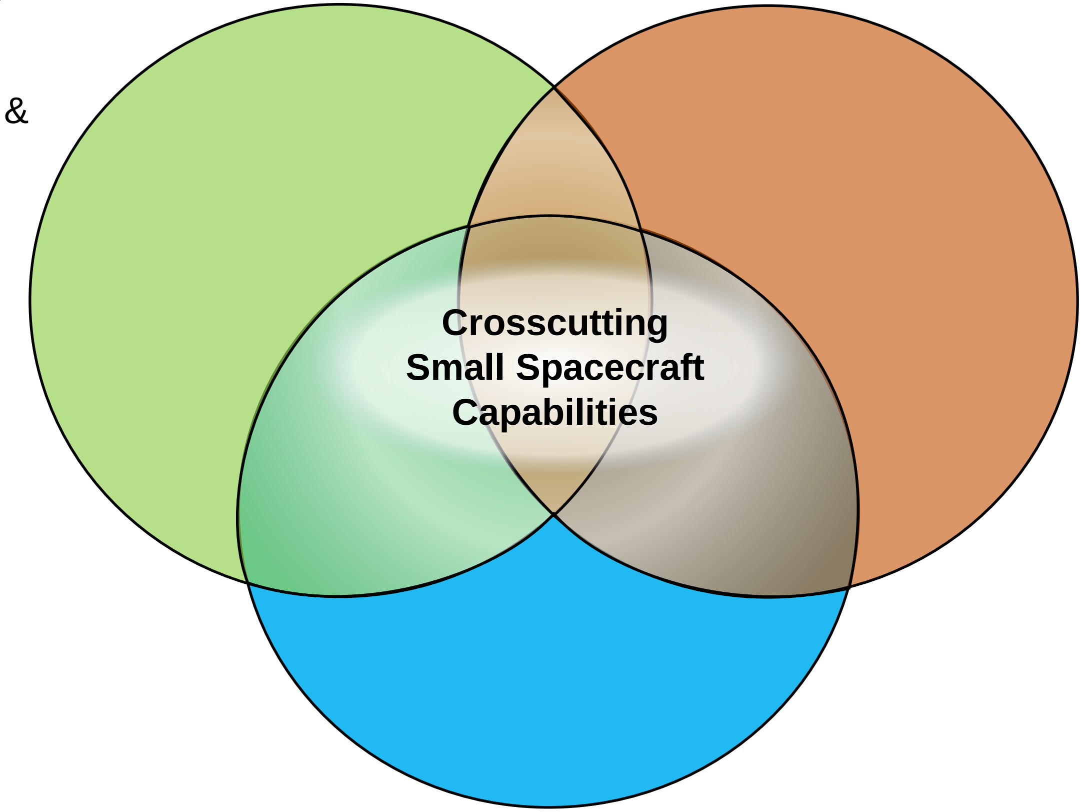
NASA’s overarching technology goals for its engagement in the small spacecraft ecosystem are to enable rapid and more affordable missions for exploration and discovery while facilitating the expansion of space commerce.

- Leveraging the risk-tolerant posture afforded by the faster timelines and lower costs, small spacecraft will enable NASA to incorporate technologies earlier and iterate through failures to **create new capacities or recreate existing capabilities at a fraction of the cost** of traditional systems.

1.2 ARCHITECTURAL APPLICABILITY

SCIENTIFIC DISCOVERY ARCHITECTURES
Earth, Planetary, Heliophysics, & Astrophysics

MOON TO MARS EXPLORATION ARCHITECTURE
Human Lunar Return, Sustained Human Presence, & First Human Mars Expedition



COMMERCIAL, NATIONAL SECURITY, & TECHNOLOGY DEMONSTRATION ARCHITECTURES

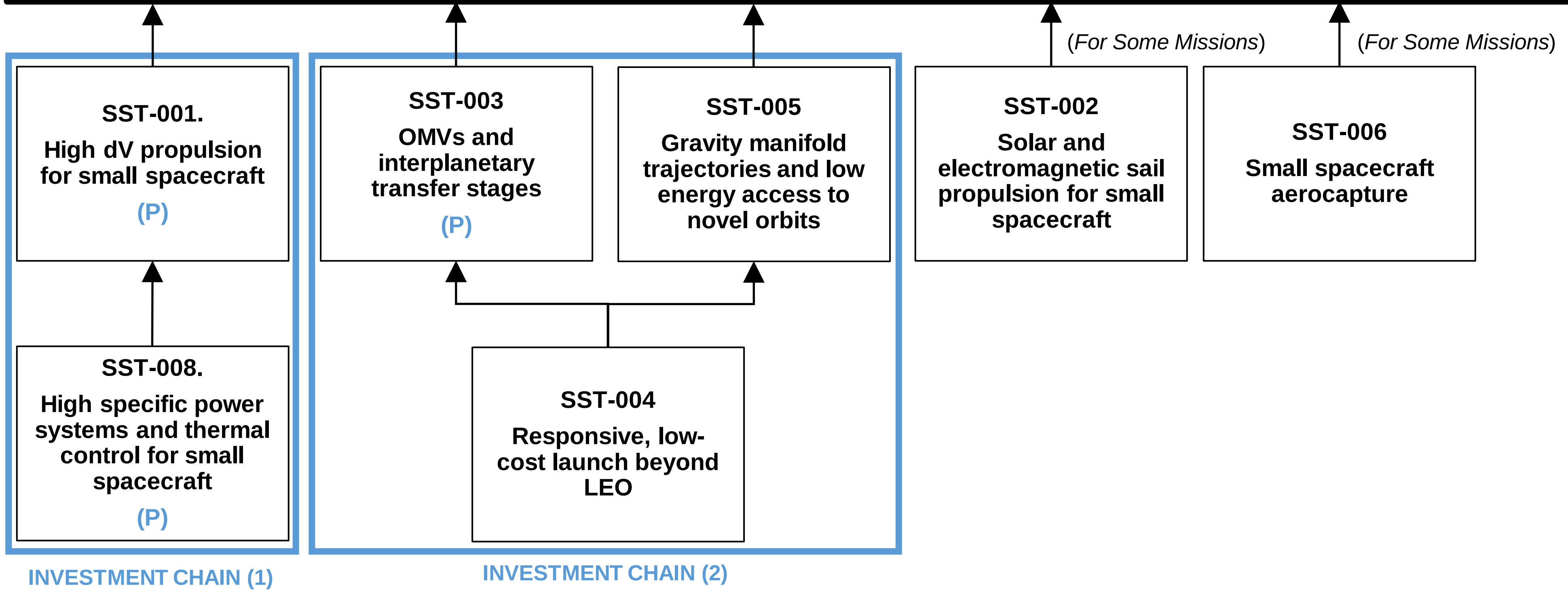
Small Spacecraft have crosscutting potential to bridge technology gaps across a wide range of architectures

1.2 OUTCOMES

	2020s	2030s	2040+
GO: Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond.	• Affordable on demand access to the Moon. (*Target: Under $15M with multiple opportunities per year.*)	• Affordable on demand access to the Moon, Mars, the rest of the inner planets, and other deep space destinations this side of the asteroid belt. (*Target: Under $15M with multiple opportunities per year.)*	• Access to the outer planets, their moons, and beyond for small missions
EXPLORE: Enable new discoveries at the Moon, Mars and other extreme locations.		• Affordable distributed missions of at least 30 to 100 networked spacecraft acting as a sensor web in deep space. (*Target: Under $10M to build and deliver each node.*)	• Affordable deep space capable distributed systems that can form multi-kilometer wide synthetic apertures and multi-kilometer long virtual telescopes. (*Target: Under $20M to build and deliver each element.*)
EXPLORE: Enable new architectures that are more rapid, affordable, or capable than previously achievable.	• Small, rapid and affordable missions competitive with traditional systems for targeted measurements at the Moon. (*Target: Under $30M, including launch, and developed in under 3 years*) • Affordable, modular, and interoperable communications, navigation, and support infrastructure with full coverage of the Moon. (*Target: Under $20M to build and deliver each network node.)* • Rapid in space test capabilities that allow a technology to move from laboratory to orbit in less than 9 months.	• Small, rapid and affordable missions competitive with traditional systems for targeted measurements at the Moon, Mars, the rest of the inner planets, and the asteroid belt. (*Target: Under $30M, including launch, and developed in under 3 years*) • Affordable, modular, and interoperable communications, navigation, and support infrastructure with full coverage of the Moon and Mars. (*Target: Under $20M to build and deliver each network node.)*	• Small spacecraft able to accompany and augment larger missions to the outer planets and their moons.

1.2 TECHNOLOGY DEVELOPMENT PATHS

OUTCOME: Affordable on demand access to the moon, Mars, the rest of the inner planets, and other deep space destinations this side of the asteroid belt. (*Target of under $15M, with multiple opportunities a year.)*

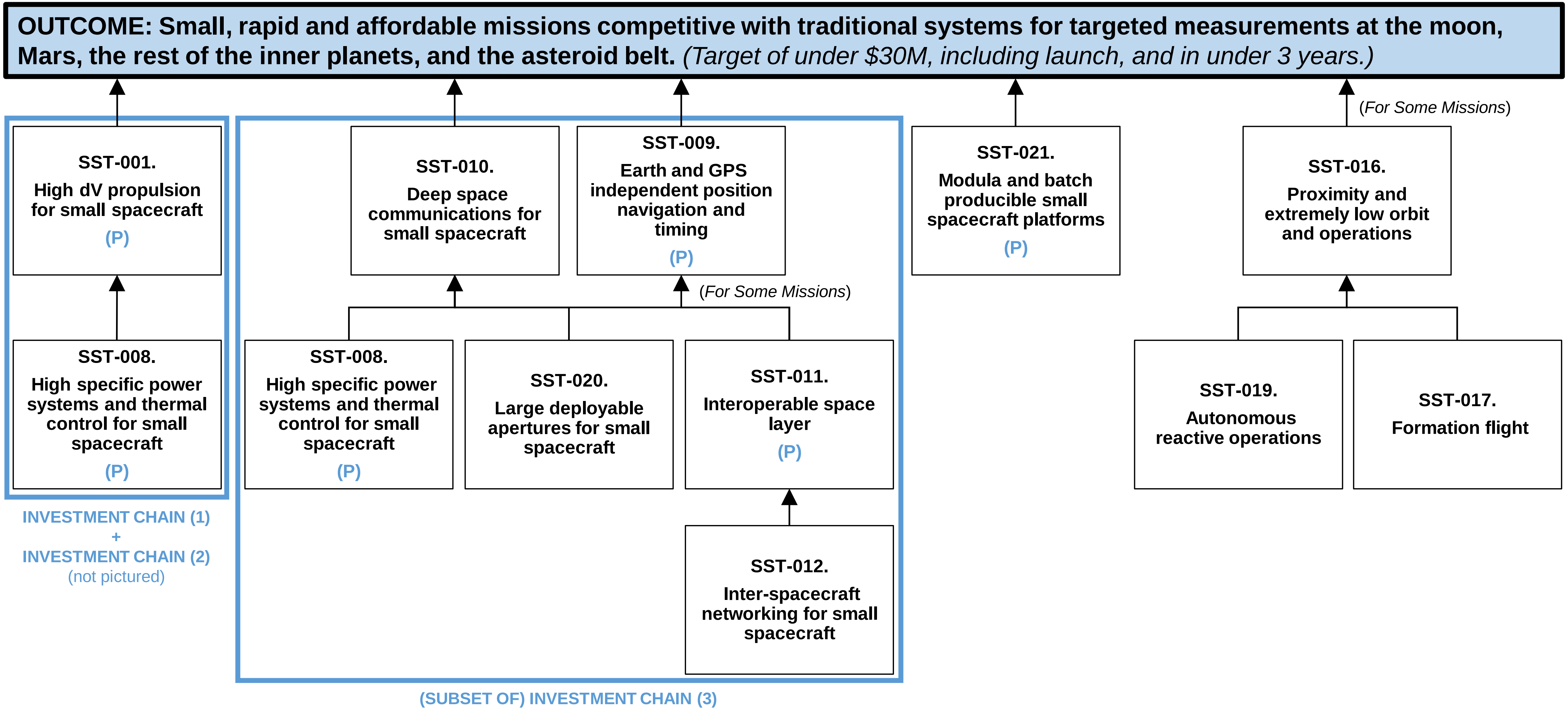


Key:

INVESTMENT CHAIN: An interdependent set of gaps that have significant influence on achieving a desired outcome

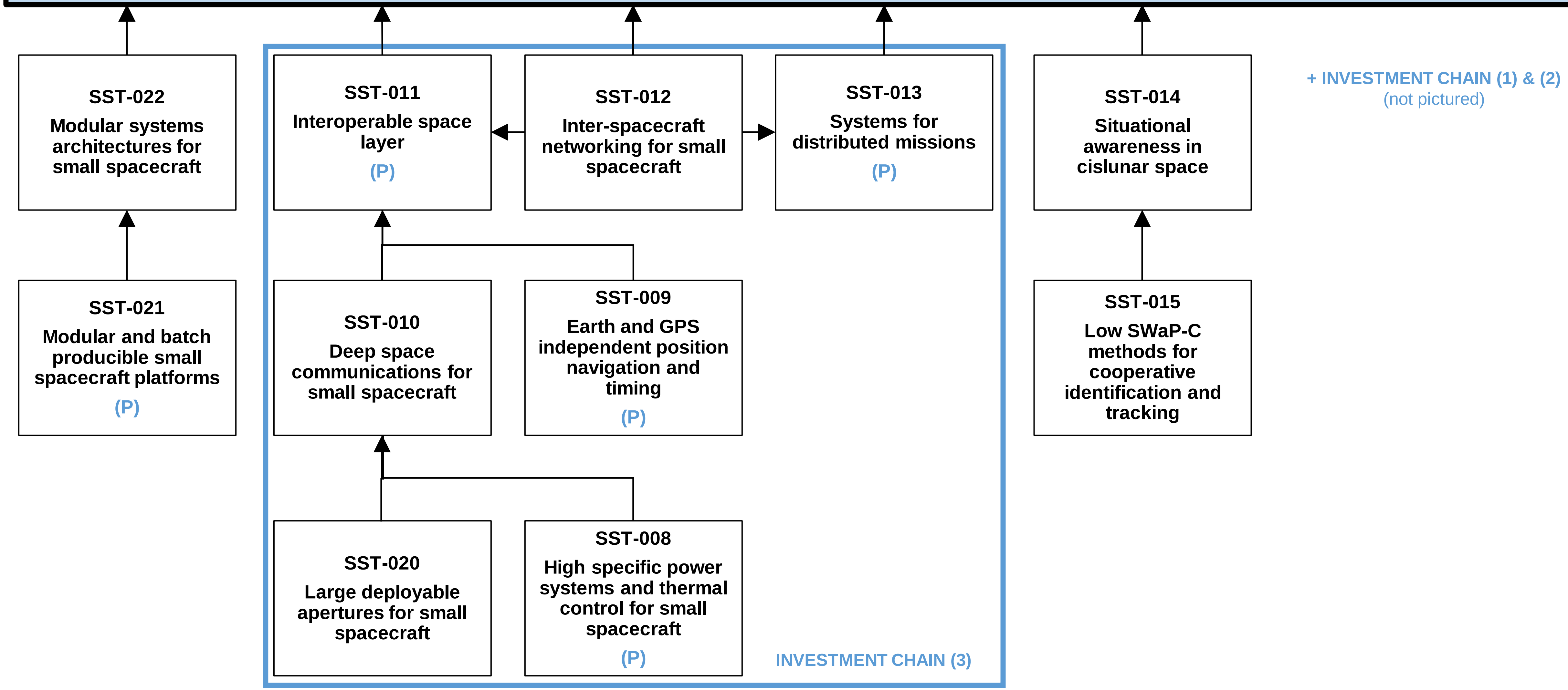
(P): A high priority investment based on its relative importance within an investment chain or on its appearance across multiple investment chains

1.2 TECHNOLOGY DEVELOPMENT PATHS



1.2 TECHNOLOGY DEVELOPMENT PATHS

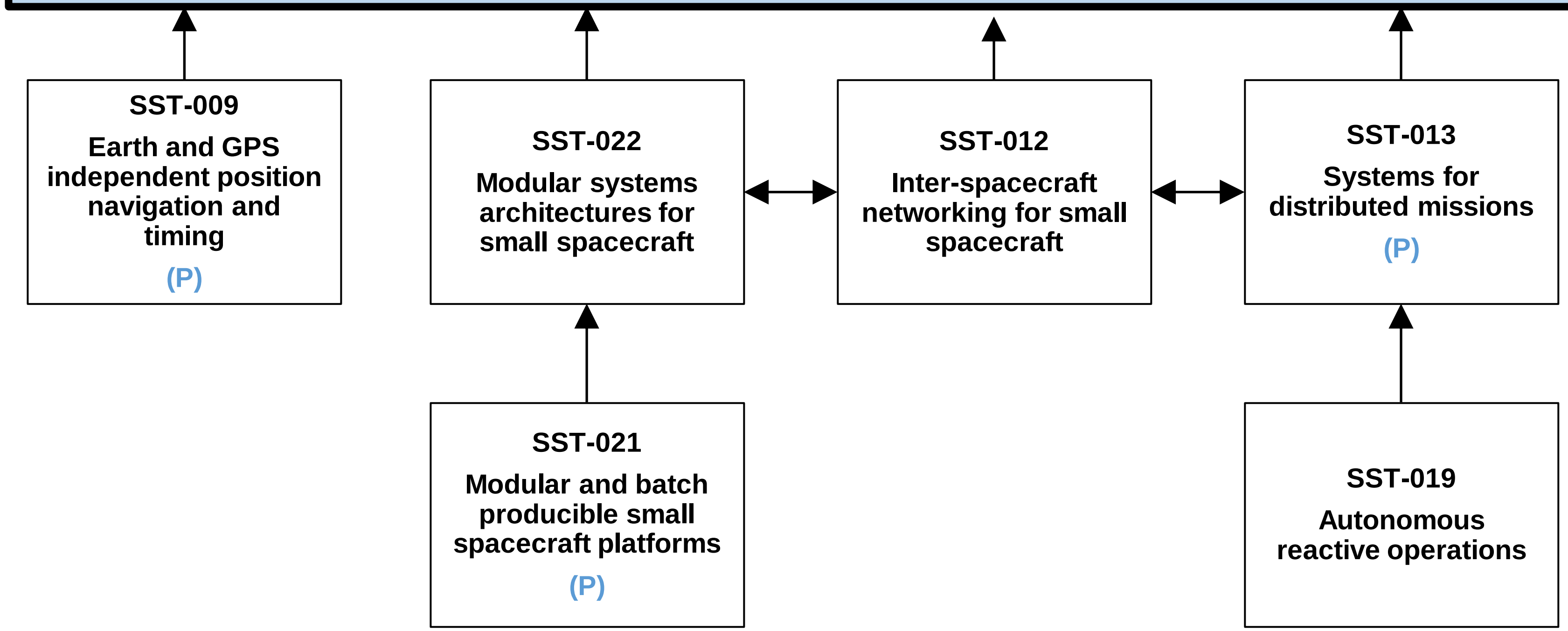
OUTCOME: Affordable, modular, and interoperable communications, navigation, and support infrastructure with full coverage of the Moon and Mars. *(Target of under $20M to build and deliver each network node.)*



BASED ON DRAFT PLAN · SUBJECT TO CHANGE

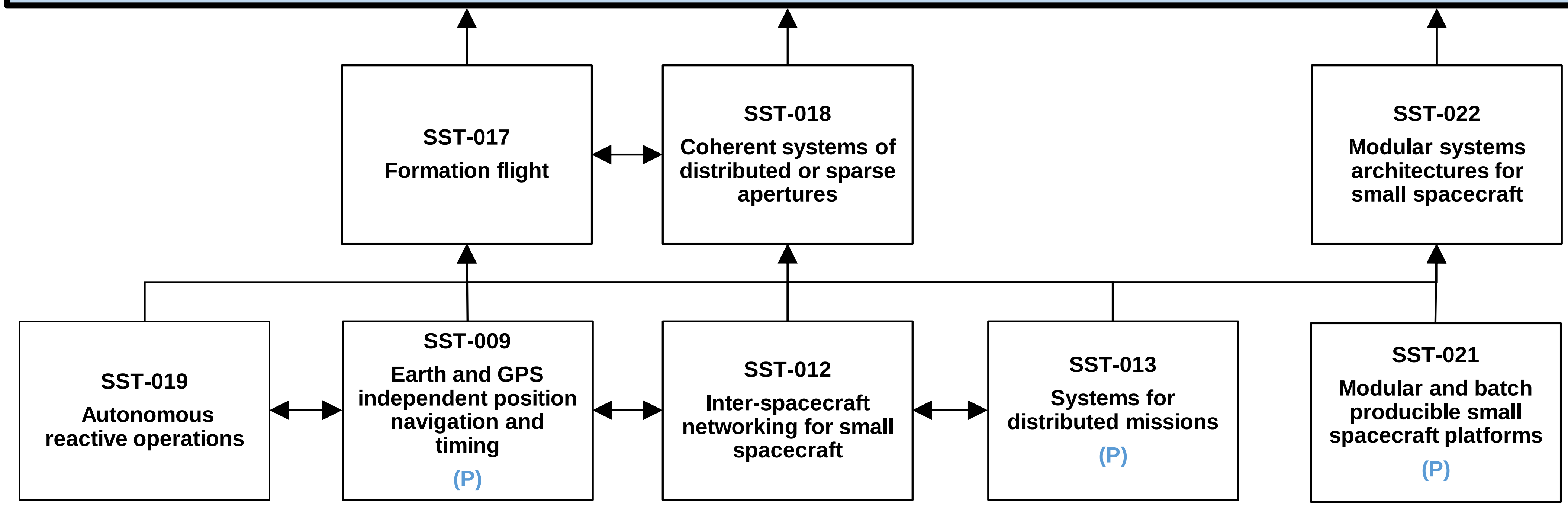
1.2 TECHNOLOGY DEVELOPMENT PATHS

OUTCOME: Affordable distributed missions of at least 30 to 100 internetworked spacecraft acting as a sensor web in deep space.
(Target of under $10M to build and deliver each network node.)



1.2 TECHNOLOGY DEVELOPMENT PATHS

OUTCOME: Affordable deep space capable distributed systems that can form multikilometer wide synthetic apertures and multikilometer long virtual telescopes. (*Target of under $20M to build and deliver each element*.)



1.2 TECHNOLOGY DEVELOPMENT PATHS

OUTCOME: Access to the outer planets, their moons, and beyond for small missions

INVESTMENT CHAIN (1)

SST-022
Modular systems architectures for small spacecraft

SST-021
Modular and batch producible small spacecraft platforms
(P)

(SUBSET OF) INVESTMENT CHAIN (2)

SST-003
OMVs and interplanetary transfer stages
(P)

SST-005
Gravity manifold trajectories and low energy access to novel orbits

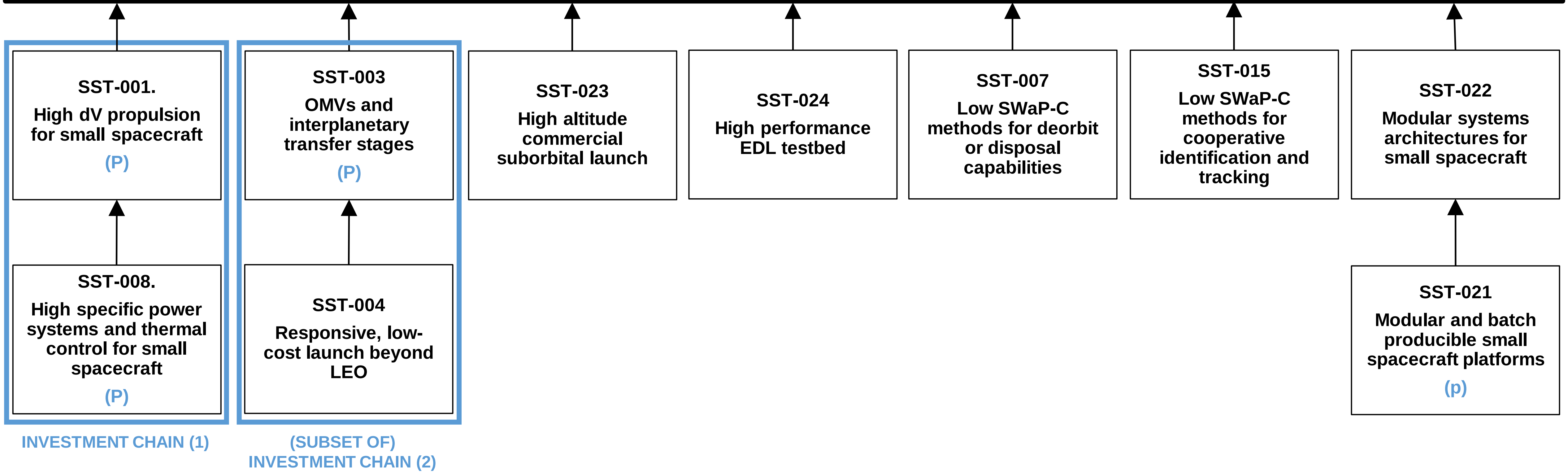
(*For Some Missions*)

SST-002
Solar and electromagnetic sail propulsion for small spacecraft

(*For Some Missions*)

SST-006
Small spacecraft aerocapture

OUTCOME: Affordable in space test capabilities that allow a technology to move rapidly from laboratory to orbit.
(Target is less than 9 months)



2.1 OVERVIEW OF TECHNOLOGY & HIGH RISK DEVELOPMENT GAPS

ID	Gap	Priority	Human Lunar Return	Sustained Human Presence	First Human Mars Expedition	Earth Science	Planetary Science	Heliophysics	Astrophysics	TECHNOLOGY DEMONSTRATION
			MOON TO MARS EXPLORATION			SCIENTIFIC DISCOVERY				
SST-001	High dV Propulsion for Small Spacecraft	(P)			→		X			X
SST-002	Solar and Electromagnetic Sail Propulsion for Small Spacecraft						→	X		
SST-003	On Orbit Maneuvering Vehicles & Interplanetary Transfer Stages	(P)		→	→		→	→		X
SST-004	Gravity Manifold Trajectories & Low Energy Access to Novel Orbits		X	X	→		X	→	X	X
SST-005	Responsive, Low-Cost Launch Beyond LEO			→	→		→		→	X
SST-006	Small Spacecraft Aerocapture				→		X			
SST-007	Low SWaP-C Deorbit or Disposal Capabilities					X				X
SST-008	High Specific Power & Thermal Control Systems for Small Spacecraft	(P)			→	X	→		→	X
SST-009	Earth and GPS Independent Position Navigation and Timing	(P)	X	X	X		X	X		X
SST-010	Deep Space Communications for Small Spacecraft				→		X	→		X
SST-011	Interoperable Space Layer	(P)	X	X	X		X			
SST-012	Inter-spacecraft Networking for Small Spacecraft			→	→	X	→	X	→	X
SST-013	Systems for Distributed Missions	(P)		→	→	X	→	X	→	X
SST-014	Situational Awareness in Cislunar Space		→	→						
SST-015	Low SWaP-C Methods for Cooperative Identification and Tracking			→		X				X
SST-016	Proximity and Extremely Low Orbit Operations with Small Spacecraft			→	→		→			
SST-017	Formation Flight with Small Spacecraft			→	→			→	X	
SST-018	Coherent Systems of Distributed or Sparse Apertures					X	→	→	X	
SST-019	Autonomous Reactive Operations					X	X	→	→	
SST-020	Large Deployable Apertures for Small Spacecraft					→	→		X	X
SST-021	Modular and Batch Producible Small Spacecraft Platforms	(P)				X	X	→		X
SST-022	Modular Systems Architectures for Small Spacecraft					X				X
SST-023	High Altitude Commercial Suborbital Launch									X
SST-024	High Performance EDL Testbed		→				X			X
SST-025	Entry Descent and Landing for Small Spacecraft						X			

KEY

NASA Pull	X
NASA Push	→
Priority Investment	(P)

Capability area	Area
TX01 & TX09	Propulsion Systems & Entry, Descent, and Landing
TX03	Aerospace Power and Energy Storage
TX05 & TX17	Communications, Navigation, and Orbital Debris Tracking & Characterization Systems Guidance, Navigation, and Control
TX10	Autonomous Systems
TX02, TX11 & TX12	Flight Computing and Avionics Software, Modeling, Simulation, and Information Processing Materials, Structures, Mechanical Systems, and Manufacturing

SST-001. HIGH dV PROPULSION FOR SMALL SPACECRAFT (P)

Enabling many of the deep space missions envisioned for multiple classes of small spacecraft requires approximately 2 to 5 km/s dV over the multiyear life of a mission. In the near term, reliably manufacturable onboard propulsion systems than can impart at least 2 km/s dV are needed. Such systems can be paired with other deep space access approaches to close mission designs. To enable that level of propulsive capability in CubeSats, systems are required that have a high impulse per unit of spacecraft and high total impulse, while remaining low power per unit of spacecraft and compatible with secondary payload launch restrictions. These systems must also be tolerant to the deep space radiation and thermal environment during missions anticipated to last multiple years. For CubeSats, use of high-density propellant may be needed to achieve the required performance within volume limitations. A similar level of performance is required for microsatellite scale systems with slightly relaxed size, weight, and power constraints but need for increased thrust to accomplish missions with those larger mass spacecraft within a reasonable timeframe. [Also see STMD-PROP-009]

SST-002. SOLAR AND ELECTROMAGNETIC SAIL PROPULSION FOR SMALL SPACECRAFT

Propulsion systems that harness the “solar wind” through photon pressure or the sun’s electromagnetic field are uniquely enabling for a number of missions that would require a prohibitive expenditure of propellant by other means. While slow to accelerate, generating thrust through interaction with the space environment affords these systems an effectively infinite dV budget over time. Solar and electromagnetic sails have long been envisioned for space weather monitoring missions that ‘hover’ closer to the sun than the gravitationally stable LaGrange points (Earth-Sun L1 in particular) to provide a greater than 50% increase in solar weather event detection times or that observe the portion of the sun rotating towards the Earth from the hard to reach Earth-Sun L5. Solar and electromagnetic sails are also enabling for missions that sit above or below the poles of the Earth (and other planets) for multiyear missions, or that leave the plane of the ecliptic all together. To support solar polar imaging, systems with the ability to reach greater than 60 degree inclination from the plane of the ecliptic are required. Sail based systems also present a credible approach to interstellar “fast transit” probes where systems able to reach escape speeds of greater than 10 astronomical units per year (AU/y) can enable missions within a human lifespan. Historically, the operational use of sail based propulsion has been prevented by the large sail areas required to close the mission analysis. The reduction in spacecraft component mass that has accompanied the “smallsat revolution” and the corresponding reduction in sail area that would be required, provides the best opportunity to field operational solar and electromagnetic mission capabilities. [See STMD-PROP-010]

SST-003. ON ORBIT MANEUVERING VEHICLES AND INTERPLANETARY TRANSFER STAGES FOR SMALL SPACECRAFT MISSIONS (P)

Small launch vehicle interplanetary transfer stages, propulsive secondary payload adaptors (SPAs), on orbit maneuvering vehicles (OMVs), and other space tug approaches allow for precision orbit / trajectory insertion for small spacecraft that might have limited propulsive capability on their own. OMVs and propulsive SPAs can expand access to uncommon orbits and destinations beyond Earth from rideshare launches to GTO. Small launch vehicle interplanetary transfer stages and propulsive SPAs provide the ability to put small spacecraft on lunar / interplanetary trajectories from regularly available low-cost launch opportunities. These approaches allow small spacecraft to reach deep space orbits that might otherwise be less archivable with current on-board propulsion capabilities or allow such spacecraft to trade significant on-board propulsive capability for more payload mass. While OMVs have been flown in Earth orbit they still require additional investment to adapt those capabilities deep space access. Similarly, small launch vehicle interplanetary transfer stages and propulsive SPAs need additional improvement in propulsive capability (on the order of 2+ km/s dV), increased operational lifetime, and navigation/guidance systems for deep space. As small spacecraft will spend extended time attached to interplanetary transfer stages and propulsive SPAs relative to LEO deployments, existing systems will need to be modified for deep space secondary payload storage and deployment with keep-alive systems, heaters, battery charging, telemetry interfaces, and other accommodations.

SST-004. GRAVITY MANIFOLD TRAJECTORIES AND LOW ENERGY ACCESS TO NOVEL ORBITS

Low energy trajectories, novel orbits and gravity manifold trajectories that make use of the influence of multiple gravitational bodies are need to enable missions that have reduced propulsive needs and that can access destinations of interest beyond Earth from GTO rideshare launches or lower cost small launch vehicles. To further lunar and Martian exploration, trajectory designs for rendezvous in the near rectilinear halo orbit (NHRO) and other unique lunar orbits are required. These trajectories support not only the primary missions but can be tailored for low energy resupply for Gateway or general cislunar access from low cost launch opportunities. These orbits that make use of the influence of multiple gravitational bodies and similar gravity manifold trajectories have the potential to enable deep space and planetary science missions that have reduced propulsive needs or that can access destinations of interest beyond Earth from GTO rideshare launches or lower cost small launch vehicles.

SST-005. RESPONSIVE, LOW-COST LAUNCH BEYOND LEO

The risk tolerant approach to small spacecraft missions is predicated on routine and affordable access to space. Rideshare opportunities on conventional launch services will continue to offer lower cost access to space and are predicted to have increasingly regular opportunities to common orbits. However, to expand the risk tolerant small spacecraft approach to deep space missions, frequent access to destinations of interest beyond Earth is required. Small launch vehicles provide direct access for a small spacecraft to the destination or orbit of interest at a time of the small spacecraft mission's choosing. Improved capability and affordability of small launch would allow an increasing number of small missions to take advantage of the mission tempo and risk posture afforded by responsive launch. In support of exploration, science, and technology demonstration missions, further expansion of these vehicle's reach beyond LEO is needed. Small launch vehicles are needed that can place nano and micro satellite class payloads on lunar and interplanetary trajectories at a price that is significantly below that of a full conventional medium lift launch vehicle and on a schedule that is driven by the small spacecraft mission.

SST-006. SMALL SPACECRAFT AEROCAPTURE

For some applications, aerocapture and aeroassist technologies can help address limitations in on board propulsion imposed by the inherent size constrains of small form factors. Small drag devices can harness atmospheric friction to bleed off excess velocity and reach or enter orbit around targets previously inaccessible for small spacecraft with limited propulsive capabilities. Rigid and deployable aeroshells need to affordably scaled, produced, and ultimately demonstrated in planetary atmospheres. Potential applications include aerocapture at Venus and Mars, aeroassist at Mars to enter orbit around the Martian moons, and aerocapture and aeroassist maneuvers at the outer planets and their moons. [See STMD-EDL-016]

SST-007. LOW SWaP-C METHODS FOR DEORBIT OR DISPOSAL CAPABILITIES

With increased use of higher orbital regimes by small spacecraft and regulatory attention on long term debris concerns, it is critical that the small spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and efficiency of small missions. Development and demonstration of low size, weight, power, and cost (SWaP-C) deorbit capabilities that are compatible with common small spacecraft form factors is required to maintain the agility of Earth orbiting small spacecraft missions while complying with new regulatory activity.

SST-008. HIGH SPECIFIC POWER SYSTEMS AND THERMAL CONTROL FOR SMALL SPACECRAFT (P)

Small spacecraft platforms impose area and volume constraints on deployable power generation systems and power storage systems. Future missions require more power for electric thrusters, active sensors, and communications systems, while simultaneously expanding into more challenging environments further from Earth and for longer duration missions. In the near term, 200 to 600 W power is needed for electric thrusters. Solar arrays intended to generate at least 100 W at Mars and other similar distance destinations for sensors, communications, and other applications will need 250 W beginning of life power at 1AU with a specific power generation of 300 W/kg and a stow rate of 350 kW/m^3. Outer planet missions would require capabilities significantly beyond the current state of the art including solar cells with unprecedented specific power generation paired with large flexible solar arrays based on solar sail or role out designs, or small nuclear power sources. As advancements in power systems increase power generation in the small densely packed CubeSat form factor, improved thermal control and waste heat rejection will become increasingly critical.

SST-009. EARTH AND GPS INDEPENDENT POSITION NAVIGATION AND TIMING (P)

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth centric aids. Future small spacecraft missions will need to autonomously determine and transmit relative and absolute orbital states as well as maintain and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions, for distributed missions comprised of small spacecraft, and for standalone small spacecraft missions beyond Earth. Access to Earth network ranging may not be available for multiple concurrent missions, missions with multiple elements, or be limited by radio capabilities for smaller missions. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g. dual use of star tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser range finding with other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost constraints of the platforms. Onboard image and data processing is required to allow for autonomous navigation. Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Improvements in chip scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate references sources are not available or feasible. [See STMD-CN-001 & STMD-CN-005]

SST-010. DEEP SPACE COMMUNICATIONS FOR SMALL SPACECRAFT

Small spacecraft missions beyond Earth required compact and low power, but high bandwidth radios for use the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio that has been operationally used at Mars. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, and Ka-Band) or optical, and can reach uplink and downlink speeds in excess of 20 Mbps with 10 meter class ground stations. Critical areas of need include improved SWaP solid state power amplifiers.

SST-011. INTEROPERABLE SPACE LAYER (P)

Exploration operations that involve multiple elements, distributed architectures that may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Landers near the lunar south pole may not have - and landers on the far side of the Moon will not have - direct line-of-sight back to Earth-based ground stations and will need to send data through a relay satellite (or Gateway). Small surface systems (including rovers or Astronauts on EVAs) on the Moon or Mars will likely not have the necessary system sizing to close a direct to Earth data link. Human surface operations may require surface to surface over the horizon communications through an orbital relay. Further, access to Earth network ranging may not be available for multiple concurrent missions, be blocked by terrain for surface operations, or be limited by radio capabilities for smaller missions. Current scientific orbiters at Mars are already used as communications relays for landers and rovers. However, these assets are aging and are not in ideal orbits to fulfill the relay function. Similarly, the Gateway will not be ideally placed to support communications functions for all lunar operations. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface or Mars may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space and at Mars. In concert with other available signals of opportunity, landed beacons, and optical navigation, small spacecraft can provide relative ranging or triangulation to aid navigation. Internetworked small spacecraft can help synchronize timing across multiple mission assets for navigation, autonomous coordination, or multipoint data collection. An ideal network will be fully interoperable, incorporating both surface and orbital nodes, low SWaP-C relays, and more capable assets as “trunk lines” back to Earth (e.g. Gateway). Operational protocols will be required that allow nodes to relay data to other nodes in a multi-hop fashion across changing network topologies. This adaptive routing can discover resources, adapt to network failures, and be tolerant of delays. Methods will be needed to distinguish traffic according to timeliness, importance, and robustness as well as queuing and routing protocols. [STMD-CN-003, STMD-CN-004, STMD-CN-007, STMD-CN-008, & STMD-CN-009]

SST-012. INTER-SPACECRAFT NETWORKING FOR SMALL SPACECRAFT

Inter-spacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP-C hardware for radio frequency and optical cross links that can reach data rates in excess of 20 Mbps with other low SWaP-C systems at hundred thousand kilometer ranges. To ensure interoperability, RF systems should be software defined and capable of operating in multiple bands (S, X, and Ka-Band). Both RF and optical systems need to be compatible with interoperable space layer protocols and capable of operating in the deep space environment. Additionally, since for the foreseeable future the majority of small spacecraft operating beyond the asteroid belt will be accompanying a primary mission and will use cross links with a larger spacecraft to communicate with Earth, spacecraft internetworking systems that can survive the harsh radiation and thermal environment of the outer planets will also be needed.

BASED ON DRAFT PLAN · SUBJECT TO CHANGE

SST-013. SYSTEMS FOR DISTRIBUTED MISSIONS (P)

Constellations of small spacecraft currently provide unprecedented persistent coverage of the Earth's surface, but the use of distributed missions for exploration infrastructure and multipoint scientific measurements beyond Earth will require new approaches to operational efficiency. Current commercial constellations use ground based semi-autonomous scheduling and orbital maintenance to decrease the need for spacecraft by spacecraft human in the loop decision making. However, each spacecraft is still individually commanded by the ground based system. For missions operating beyond Earth, the spacecraft will need to be operated as a single unit. Enabling command and control capabilities within the flight element of the distributed mission will allow control of an otherwise impractical number of small spacecraft as well as decreased operational costs for missions with fewer spacecraft. Two general categories of capability are needed, the ability to command and control a formation of three or more spacecraft as a unit and the ability to command and control a constellation or sensor web of 30 to 100 spacecraft as a unit.

SST-014. SITUATIONAL AWARENESS IN CISLUNAR SPACE

The vast majority of current commercial interests and government missions operate in near Earth orbits. To date both NASA and the commercial spaceflight industry have enjoyed strong investment in near Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grow and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.

SST-015. LOW SWaP-C METHODS FOR COOPERATIVE IDENTIFICATION AND TRACKING

With increased demands on existing space situational awareness capabilities and regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs low SWaP-C identification and tracking aids. Employing such methods would allow the community to operate with lower risk to all spacecraft in orbit without negatively impacting the efficiency of small missions. There is a clear need to develop and demonstrate low cost and complexity identification and tracking aids that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystem. Technologies used for identification and tracking aids in LEO may also have extensibility to the growing number of cislunar missions.

SST-016. PROXIMITY AND EXTREMELY LOW ORBIT OPERATIONS WITH SMALL SPACECRAFT

Small spacecraft can overcome inherent aperture size limitations through deployable systems, synthetic apertures, or novel operational means. A smaller aperture and low power instrument will suffice when placed in close proximity to a small body or when flying in an extremely low orbit over a planetary surface. Potential mission concepts call for sensors to be placed within 10 km or less of an airless moon, this can be accomplished through tethered systems or spacecraft in terrain following orbits. Proximity operations with asteroids and other small bodies can also reveal valuable information about the gravitational field, magnetic field, and overall composition of the object. Similar capabilities enable external inspection of human exploration systems and other high value space assets by small spacecraft. Extremely low orbit operations requires autonomous navigation systems, autonomous maneuver planning, and hazard / fault detection and recovery systems that are compatible with small spacecraft platforms. Proximity operations with small bodies will further require low SWaP-C relative navigation sensors for cooperative artificial targets, non-cooperative artificial targets (such as a non-responsive satellite), and non-cooperative natural targets (such as asteroids and comets). [See STMD-OSAM-014]

SST-017. FORMATION FLIGHT WITH SMALL SPACECRAFT

Multiple small spacecraft operating in coordinated orbital geometries or performing relative station keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft require sensors and maneuvering systems that are low SWaP-C. [See STMD-OSAM-009]

SST-018. COHERENT SYSTEMS OF DISTRIBUTED OR SPARSE APERTURES

At some wavelengths sparse and distributed apertures can achieve resolutions and wave form fidelity on par with a solid aperture system of an equivalent size (e.g. radio telescopes). Large systems of distributed small spacecraft can serve as nodes in a sparse, synthetic aperture and more generally for very long base line interferometry. To realize this capability, improvements are needed in multiple technical areas including small spacecraft formation flight, coordinated station-keeping, relative orbital state and timing exchange, precision attitude control systems, inter-spacecraft networking, distributed mission systems, and onboard data processing.

SST-019. AUTONOMOUS REACTIVE OPERATIONS WITH SMALL SPACECRAFT

Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human in the loop control will be required to process input onboard and execute correct responses autonomously. These sensor driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well the detection and reaction to transient events for observation (such as would be required for sampling a plume from Enceladus). [See STMD-ASR-001, STMD-ASR-003, STMD-ASR-004, STMD-ASR-005, STMD-ASR-014]

SST-020. LARGE DEPLOYABLE APERTURES FOR SMALL SPACECRAFT

Small spacecraft are inherently size constrained. Higher bandwidth or longer range communications and improved radio frequency remote sensing capabilities require deployable apertures to overcome the limited surface area and volume available for fixed antennas. Given the tight volume constraints of CubeSats and other small spacecraft, deployable systems for these platforms need to be highly volumetrically efficient and may employ novel configurations or deployment mechanisms relative to their larger brethren. Some examples include thin film reflectors, inflatable antennas, shape memory alloy based systems, and deployable flat panel antennas that fold along the sides of or wrap around the spacecraft prior to deployment (e.g. ISARA & MarCO). Risk tolerant small spacecraft may also make use of simplified low-cost systems that would generally not be considered for traditional spacecraft, a current example is the widespread use of CubeSat antennas built from metallic tape measures. At the other end of the spectrum, advanced concepts have also looked at deployable optical apertures for both laser communications and remote sensing applications. Modular optics deployed from the surface or interior of a small spacecraft can be used to increase the diameter of the primary mirror or increase the length of the optical path and improve the performance of an otherwise constrained system.

SST-021. MODULAR AND BATCH PRODUCIBLE SMALL SPACECRAFT PLATFORMS (P)

Interchangeable hardware and software with standardized interfaces enables spacecraft to be built up from "plug and play" components. Standardization of subsystem interfaces for CubeSats and larger microsatellites can expand upon the vibrant market that has developed around the CubeSat form factor. Expanding the reach of small spacecraft to new destinations without losing the speed and agility that has made the platform highly successful in LEO requires affordable and adaptable methods of addressing both challenging new radiation and thermal environments (such as adding affordable radiation tolerance to consumer electronics) and unique mission needs. The adaptability introduced by interchangeable subsystems facilitates introduction of new capabilities and tailoring of spacecraft designs for novel applications without requiring significant modifications to commercial-off-the-shelf platforms. This approach can be used to increase reliability and introduce unique functionality for deep space missions without sacrificing the ability to leverage innovations in the commercial sector. Subsystem modularity can also reduce complexity in spacecraft manufacturing. Partnership with industry on batch production of spacecraft will be required to fully realize the potential for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications architectures, constellations, and sensor web applications. Planned Heliophysics missions call for 30 to 100 spacecraft; the ability to assemble relatively large 'batches' of deep space capable spacecraft in the span a couple of years and at an affordable unit price will be critical to achieving the manufacturing throughput required. Exploration pathfinding, Planetary Science, and technology development missions would also benefit from regular production of low-cost and shorter lead time (less than 12 months) deep space capable platforms with standardized interfaces for key systems.

SST-022. MODULAR SYSTEMS ARCHITECTURES FOR SMALL SPACECRAFT

Spacecraft assembled from modular components lend themselves to software defined systems and modularity at the architectural level. Small spacecraft can fulfill discrete and modular roles within a larger system architecture, enabling new capabilities and operational schemes. Assigning individual system-level functions, such as communications or sensing, to multiple spacecraft enables a constellation of smaller spacecraft to synthetically function as a single larger one. Unlike a single spacecraft, the open architecture allows for continuous reassignment of functions, perpetual upgrade/replacements, and modular expansion of the system. Each spacecraft becomes a node that can plug and play into the larger system. Each component or spacecraft fulfills individual functions that can be hot-swapped to meet different needs. Such an approach enables missions that can switch out instruments, upgrade exhausted components, and expand iteratively. Modular systems allow both adaptive spacecraft and adaptive missions that can vary their objectives and risk tolerance on the fly.

SST-023. HIGH ALTITUDE COMMERCIAL SUBORBITAL LAUNCH

Commercial suborbital vehicles are currently providing valuable flight test capabilities for technologies relevant to exploration, discovery, and space commerce. Additional vehicle performance and payload accommodations can further expand the applicability of this potentially rapid and lower-cost test platform. There is existing demand for higher altitude suborbital flights in excess of 160 km that can carry a minimum of 100kg and a desired 200 kg of test payload in a volume minimum of 1.2m x 0.45m x 0.45m and a desired 1.2m x 0.9m x 0.9m payload volume. There is demand for these flight to be able to release a 100-200 kg class test article during flight, expose the payload(s) to the space environment, or provide multiple payloads / sensors with unobstructed external vehicle access for the entire flight profile. Such a testbed should be capable of flying at least once a month for under $2M. In addition to release of test articles during flight, there is also demand for systems that can expose a payload to hypersonic free flow or augment a payload's ballistic decent to achieve velocities more consistent with orbital entry conditions for Mars or Earth reentry. Increased altitude flights also afford additional microgravity test time for payloads not requiring space exposure or release. Very high-altitude suborbital launch vehicles with sufficient payload volume can provide risk reduction testing of deployable structures or other processes that cannot occur in terrestrial gravity and take longer durations than current microgravity test capabilities provide.

SST-024. HIGH PERFORMANCE EDL TESTBED

Enhanced suborbital launch vehicle capability is required for closed-loop testing of precision landing and hazard avoidance technologies during propulsive descent and landing on trajectories and at descent rates that are dynamically-relevant to operational landings on the Moon and Mars. Expanding upon current capabilities, higher performance suborbital EDL testbeds should be able to carry large payloads on the order of 200 kg while achieving at least 2 km of altitude and providing downrange translation adequate to test powered descent guidance and terminal divert capabilities. The current state of the art method of running a ’stock’ GN&C and supervisory safety system in parallel / stand-by during the entire propulsive flight profile should be considered for the new class of higher performance suborbital vehicles. [See STMD-EDL-017]

SST-025. ENTRY DECENT AND LANDING SYSTEMS FOR SMALL SPACECRAFT

Small spacecraft have not had the ability to traverse atmospheres or land on planetary bodies. Mass and volume efficient entry decent and landing (EDL) systems can expand the reach and use of small spacecraft. Low-mass aeroshells, such as inflatables, that can be packed into CubeSat and small spacecraft form factors are required to enable both small spacecraft aerocapture and EDL. Reliable deployment subsystems and control avionics are needed and may come from from new design and production approaches. Additionally, low SWaP-C precision landing and hazard avoidance systems and associated algorithms that can operate on low SWaP-C avionics can expand small spacecraft capabilities to rapid and lower cost landed missions. [See STMD-EDL-016]

NASA